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(54) **EFFICIENT, FLEXIBLE MOTION ESTIMATION ARCHITECTURE FOR REAL TIME MPEG2 COMPLIANT ENCODING**

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(52) **U.S. Cl.** **375/240.16**
(58) **Field of Search** 348/384, 390, 348/400–403, 405, 407, 409–413, 415, 416, 419, 420, 699; 382/232, 236, 238; 375/240.12, 240.13, 240.14, 240.15, 240.16, 240.24; H04N 7/137, 7/32

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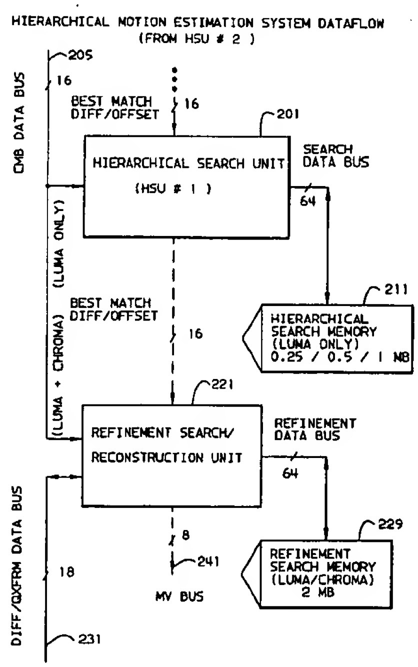
(57) **ABSTRACT**

Temporal compression of a digital video data stream with hierarchically searching in at least one search unit for pixels in a reference picture to find a best match for the current macroblock. This is followed by constructing a motion vector between the current macroblock and the best match macroblock in the reference picture.

14 Claims, 10 Drawing Sheets



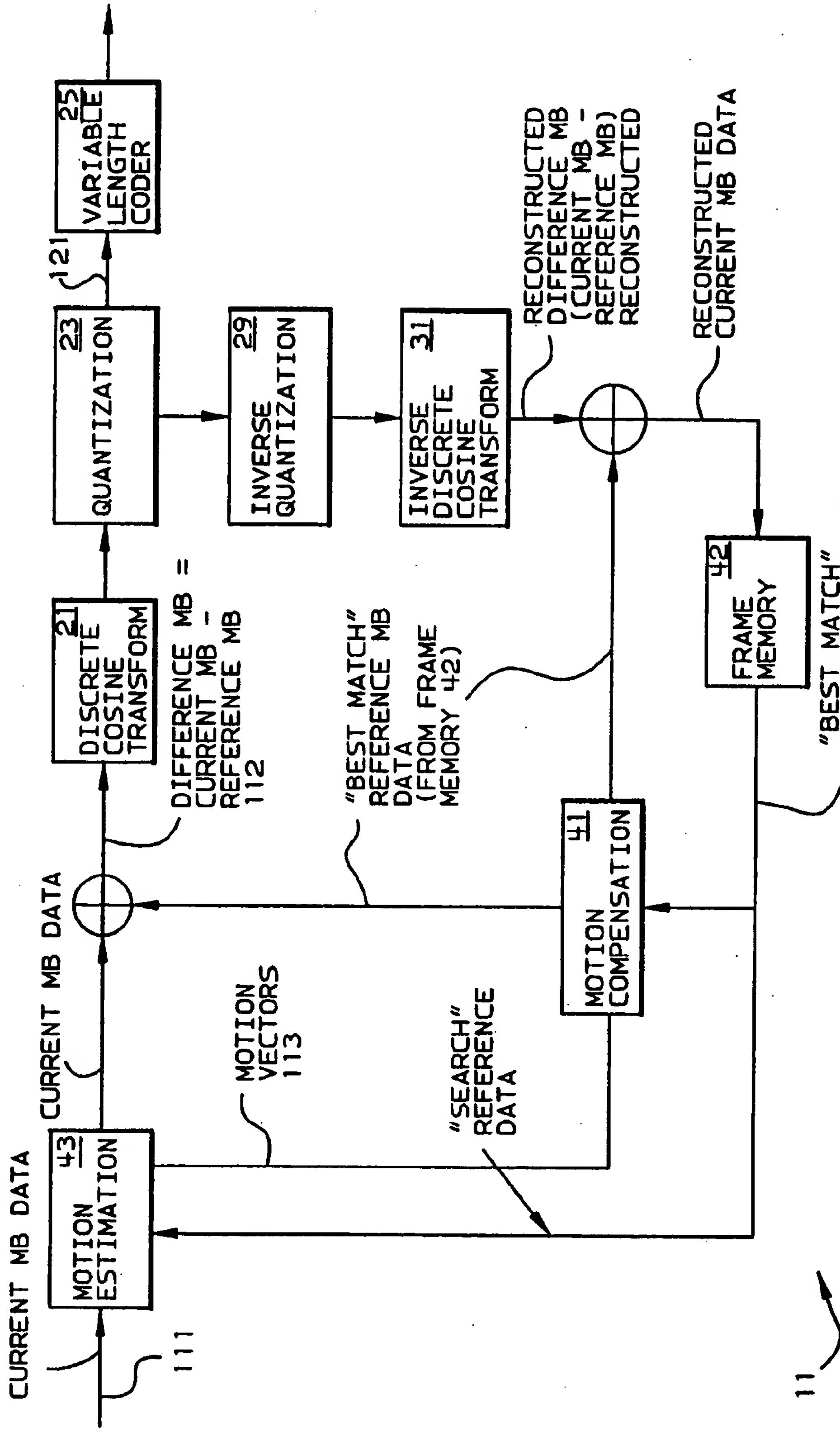

CURRENT MB DATA
111
MOTION ESTIMATION 43
CURRENT MB DATA
MOTION VECTORS 113
"SEARCH" REFERENCE DATA
MOTION COMPENSATION 41
"BEST MATCH" REFERENCE MB DATA
DIFFERENCE MB = CURRENT MB - REFERENCE MB 112
DISCRETE COSINE TRANSFORM 21
"BEST MATCH" REFERENCE MB DATA (FROM FRAME MEMORY 42)
QUANTIZATION 23
121
VARIABLE LENGTH CODER 25
INVERSE QUANTIZATION 29
INVERSE DISCRETE COSINE TRANSFORM 31
RECONSTRUCTED DIFFERENCE MB (CURRENT MB - REFERENCE MB) RECONSTRUCTED
RECONSTRUCTED CURRENT MB DATA
FRAME MEMORY 42
"BEST MATCH" REFERENCE MB DATA
11

FIGURE 1

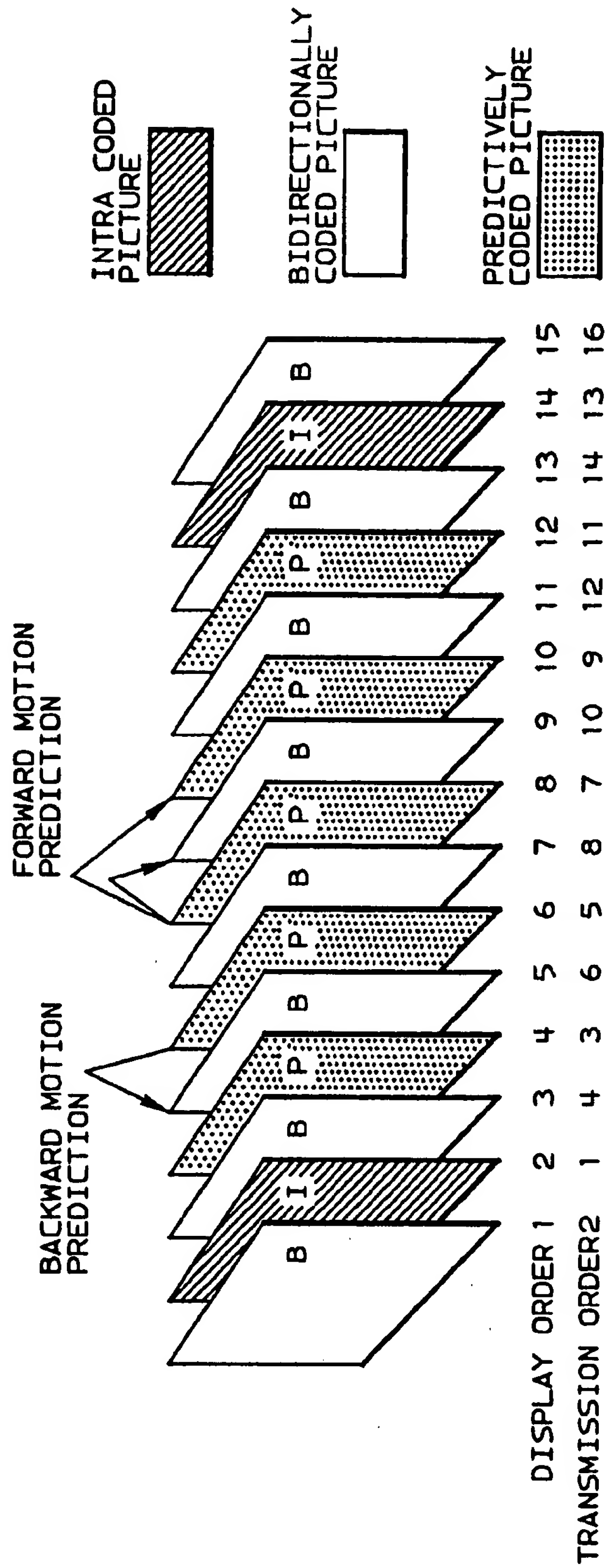

INTRA CODED PICTURE
BIDIRECTIONALLY CODED PICTURE
PREDICTIVELY CODED PICTURE
FORWARD MOTION PREDICTION
BACKWARD MOTION PREDICTION
B I B P B P B P B P B P B I B
DISPLAY ORDER 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
TRANSMISSION ORDER2 1 4 3 6 5 8 7 10 9 12 11 14 13 16

FIGURE 2

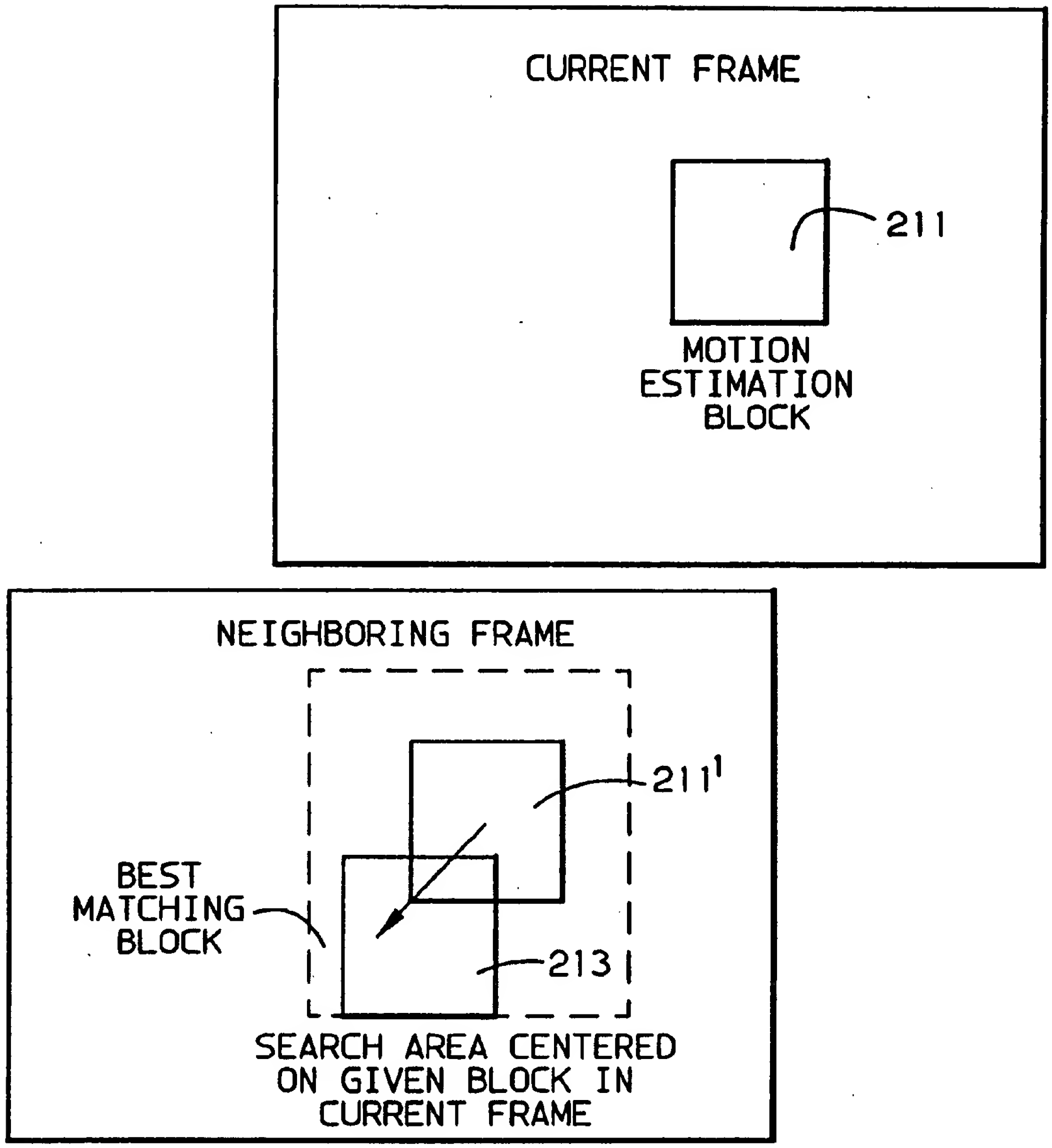
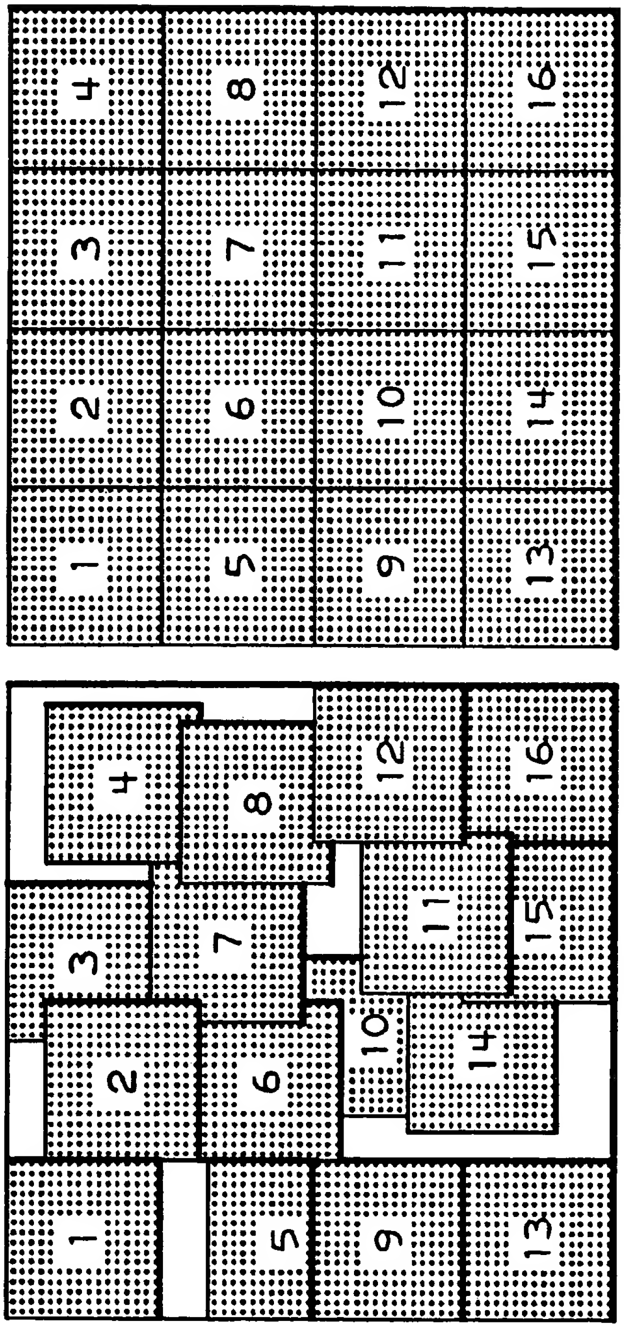

CURRENT FRAME
211
MOTION
ESTIMATION
BLOCK
NEIGHBORING FRAME
211'
BEST
MATCHING
BLOCK
213
SEARCH AREA CENTERED
ON GIVEN BLOCK IN
CURRENT FRAME

FIGURE 3



BLOCKS OF PREVIOUS PICTURE USED TO PREDICT CURRENT PICTURE.

CURRENT PICTURE AFTER USING MOTION VECTORS TO ADJUST PREVIOUS PICTURE BLOCK POSITIONS.

FIGURE 4

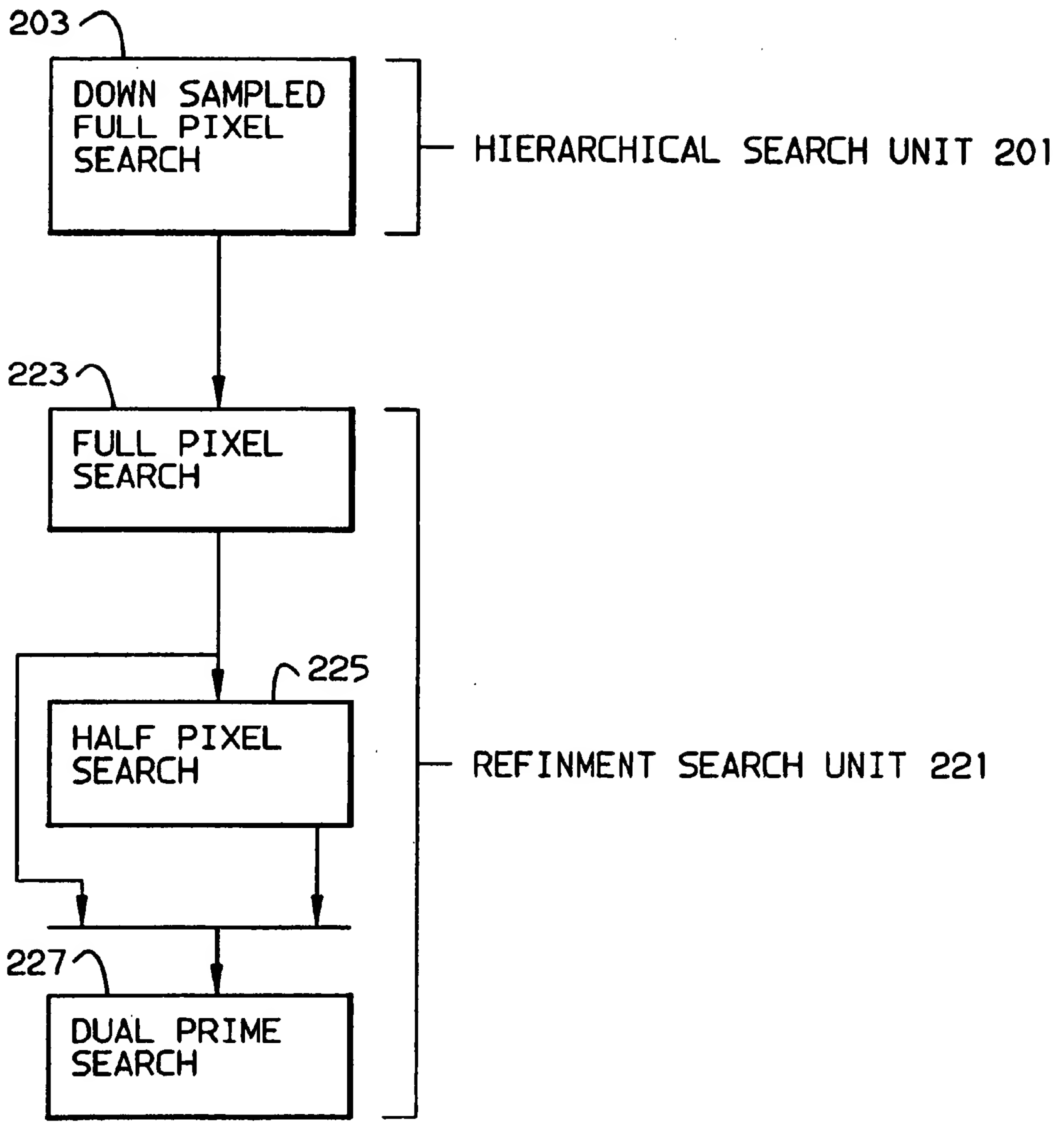

203
DOWN SAMPLED FULL PIXEL SEARCH
HIERARCHICAL SEARCH UNIT 201
223
FULL PIXEL SEARCH
225
HALF PIXEL SEARCH
REFINMENT SEARCH UNIT 221
227
DUAL PRIME SEARCH

FIG. 5

HIERARCHICAL MOTION ESTIMATION SYSTEM DATAFLOW

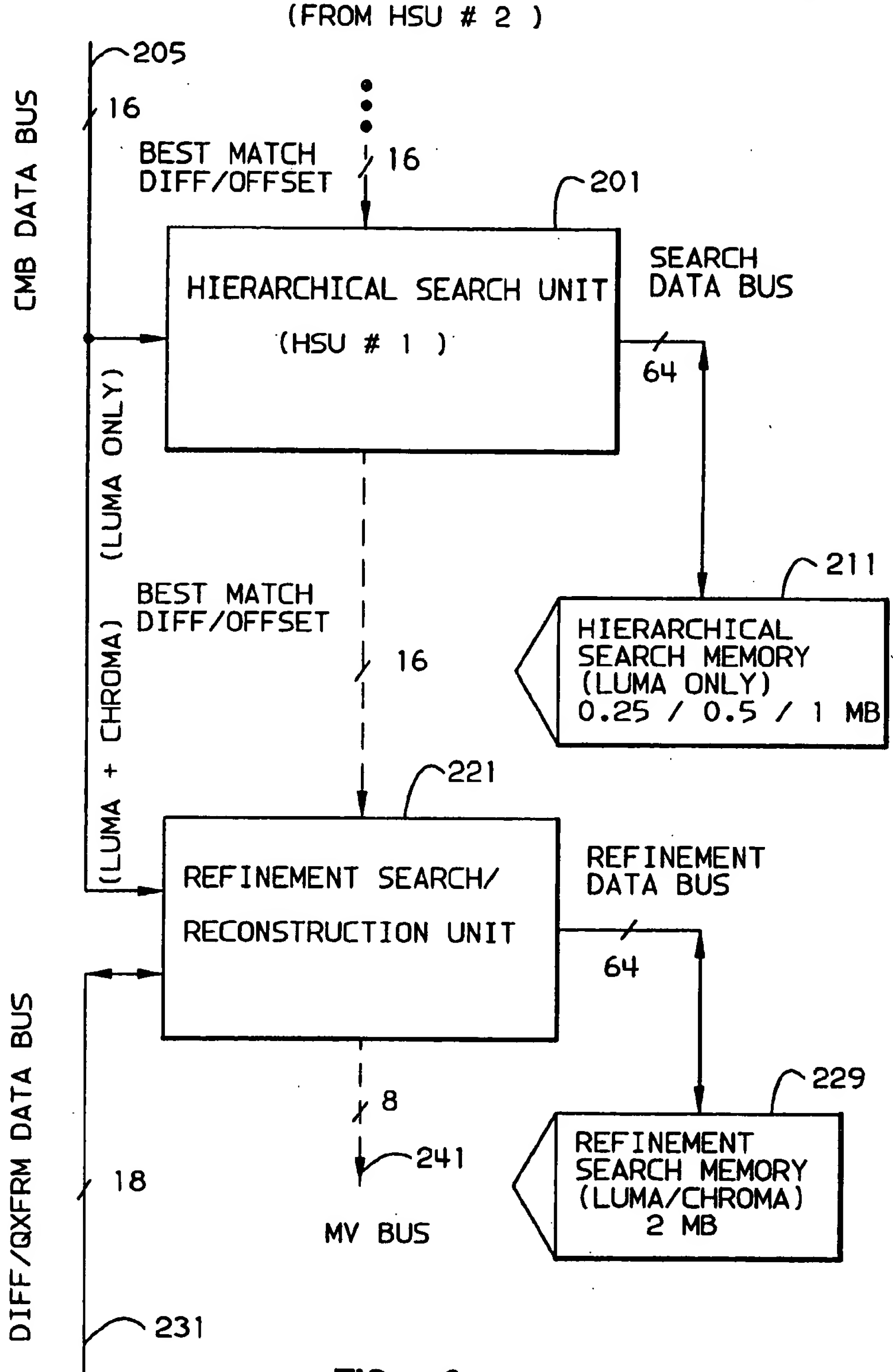


FIG. 6

HIERARCHICAL SEARCH UNIT DATAFLOW

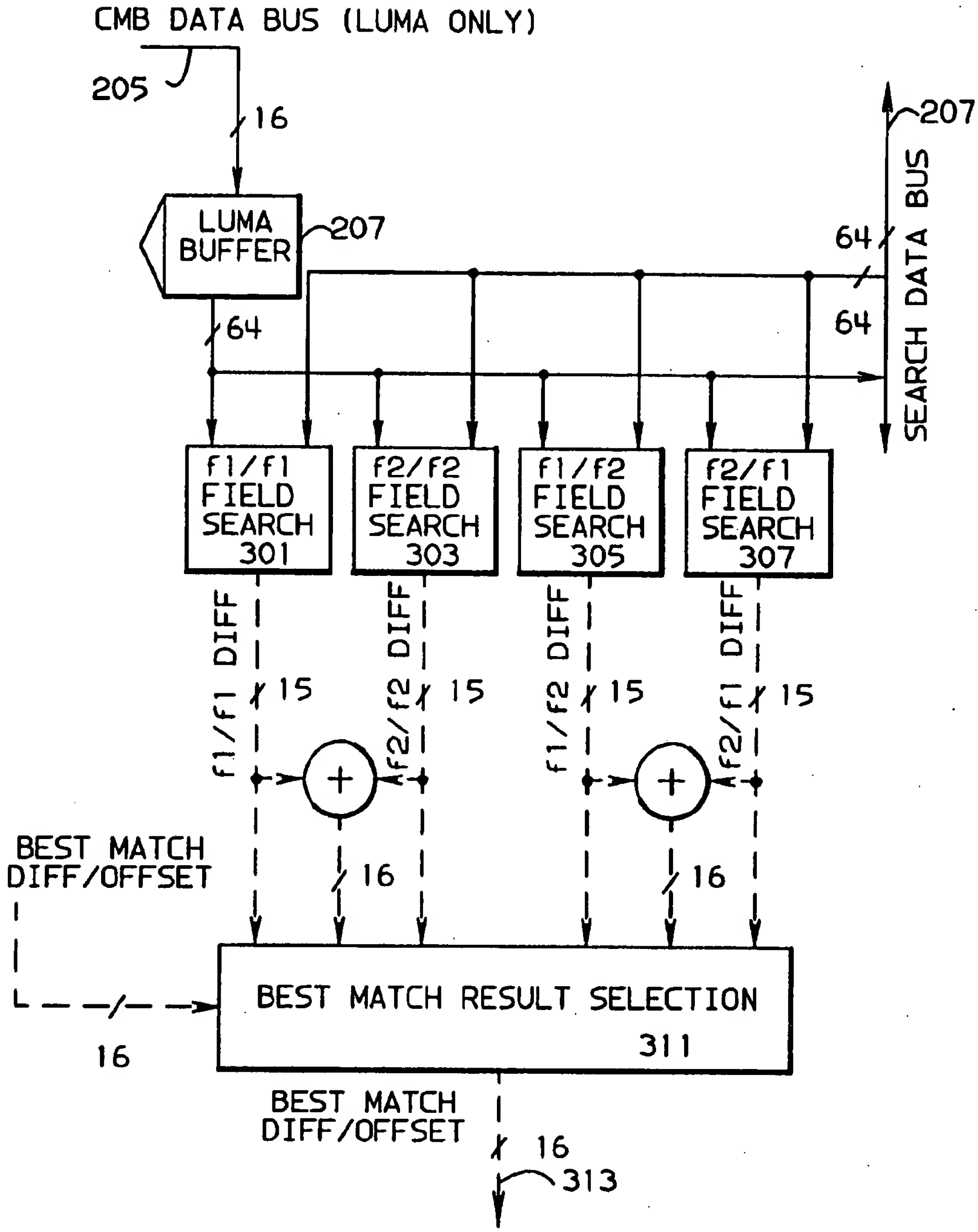


FIG. 7

REFINEMENT SEARCH/RECONSTRUCTION UNIT DATAFLOW

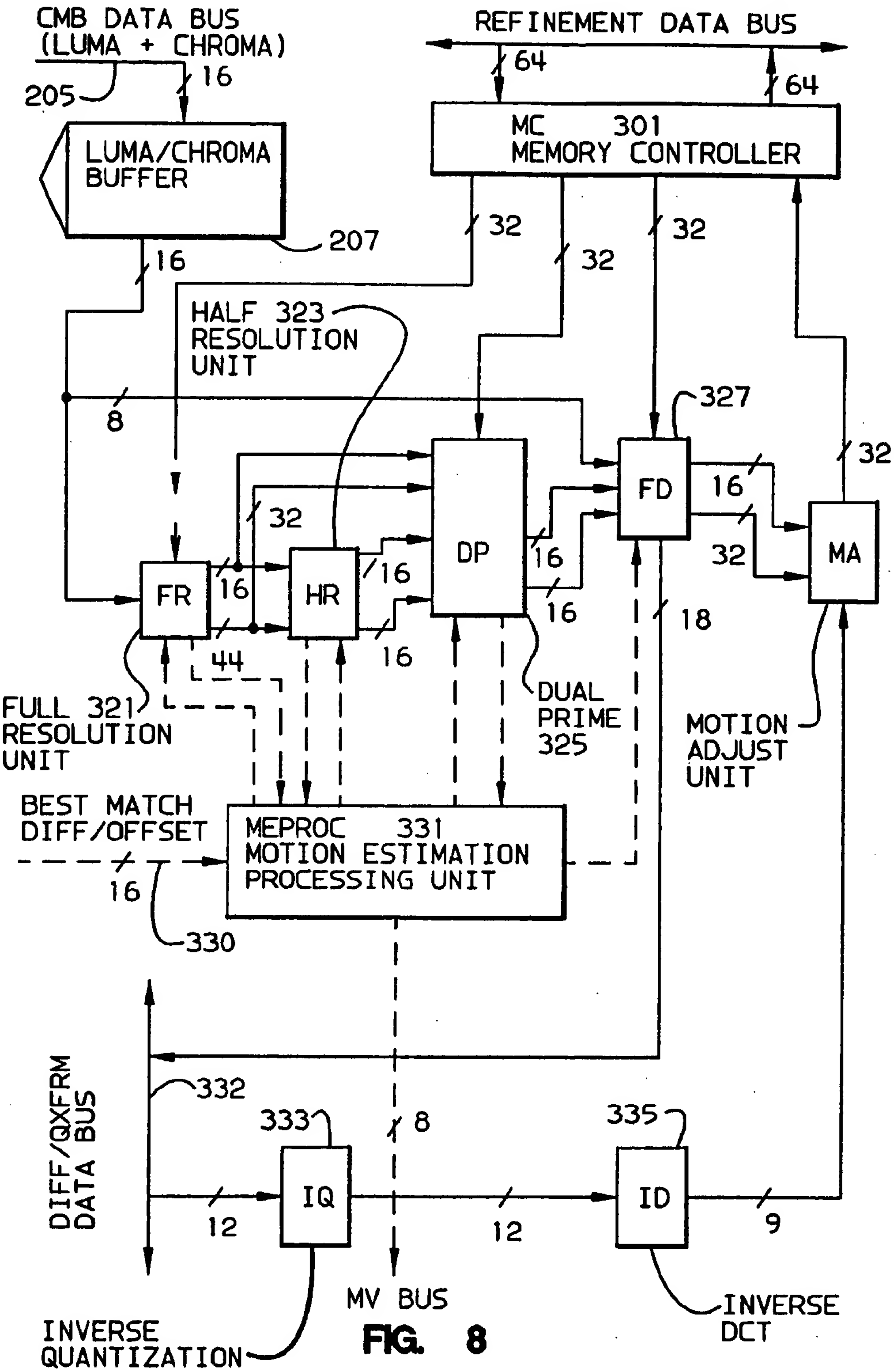


FIG. 8

SEARCH MODE	PICTURE STRUCTURE	PICTURE TYPE	MOTION EST. OPTIONS	# OF SEARCHES	SEARCH TYPES	SEARCH SIZE
HIER	INTERLACED	I,P	NO DP,1REF	1	OP	+/- 4H +/- 1V
HIER	INTERLACED	I,P	NO DP,2 REF	2	OP, SP	+/- 4H +/- 1V
HIER	INTERLACED	I,P	DP,2 REF	2	OP, SP	+/- 4H +/- 1V
HIER	INTERLACED	B	NO DP,2 REF	6	OP(PR), SP(PR), OP(FR), SP(FR), OP(BR), SP(BR)	+/- 4H +/- 1V
HIER	PROGRESSIVE	I,P	NO DP	5	f1/f2, f1/f1 f2/f1, f2/f2, FRAME	+/- 4H +/- 1V
HIER	PROGRESSIVE	I,P	DP	3	F1/F2' F2/F1' FRAME	+/- 4H +/- 1V

FIG.9

HIER	PROGRESSIVE	B	NO DP	9	f1/fX(PR), f2/fX(PR), FRAME(PR), f1/fX(FR), f2/fX(FR), FRAME(FR), f1/fX(BR), f2/fX(BR), FRAME(BR)	+/- 4H +/- 1V
NON-HIER	INTERLACED	I,P	NO DP,1 REF	1	OP	+/- 8H +/- 7V
NON-HIER	INTERLACED	I,P	NO DP,2 REF	2	OP, SP	+/- 8H +/- 7V
NON-HIER	INTERLACED	I,P	DP,2 REF	1	OP	+/- 8H +/- 7V
NON-HIER	PROGRESSIVE	I,P	NO DP	5	f1/f1, f1/f2, f2/f1, f2/f2, FRAME	+/- 8H +/- 7V
NON-HIER	PROGRESSIVE	I,P	DP	5	f1/f1, f1/f2, f2/f1, f2/f2, FRAME	+/- 8H +/- 7V

FIG.10

EFFICIENT, FLEXIBLE MOTION ESTIMATION ARCHITECTURE FOR REAL TIME MPEG2 COMPLIANT ENCODING

FIELD OF THE INVENTION

The invention relates to real time motion estimation in MPEG2 compliant digital video encoding. Motion estimation is the compression between pictures through the use of motion vectors. According to the invention temporal compression of a digital video data stream is carried out by hierarchically searching in at least one search unit for pixels in a reference picture to find a best match macroblock for the current macroblock. This is followed by constructing a motion vector between the current macroblock and the best match macroblock in the reference picture.

BACKGROUND OF THE INVENTION

Within the past decade, the advent of world-wide electronic communications systems has enhanced the way in which people can send and receive information. In particular, the capabilities of real-time video and audio systems have greatly improved in recent years. In order to provide services such as video-on-demand and videoconferencing to subscribers, an enormous amount of network bandwidth is required. In fact, network bandwidth is often the main inhibitor to the effectiveness of such systems.

In order to overcome the constraints imposed by networks, compression systems have emerged. These systems reduce the amount of video and audio data which must be transmitted by removing redundancy in the picture sequence. At the receiving end, the picture sequence is uncompressed and may be displayed in real time.

One example of an emerging video compression standard is the MPEG standard. Within the MPEG standard, video compression is defined both within a given picture and between pictures. Video compression within a picture is accomplished via a process of discrete cosine transformation, quantization, and run length encoding. Video compression between pictures is accomplished via a process referred to as motion estimation, in which a motion vector is used to describe the translation of a set of picture elements (pels) from one picture to another. These motion vectors are themselves encoded.

Motion estimation algorithms are repetitive functions which require a large amount of computational power when effectively implemented. This is especially true if motion estimation is being performed in a real time video transmission environment. In addition, two important constraints imposed by system designers are the card/board area consumed by and cost of the components required to perform the video compression function. This particularly includes the amount of DRAM and/or SRAM required to store reference picture data. A need exists for a robust motion estimation dataflow which maximizes computational power to satisfy real time encoding requirements and minimizes the amount of chip area consumed to implement it. There is also a clear need to make the motion estimation dataflow scalable so that numerous system cost points can be attained.

OBJECTS OF THE INVENTION

It is one objective of the invention to provide a robust motion estimation dataflow which maximizes computational power to satisfy real time encoding requirements and minimizes the amount of chip area consumed to implement it.

It is a further objective of the invention to provide the motion estimation dataflow scalable so that numerous system cost points can be attained.

It is a still further objective of the invention to provide a hierarchical motion estimation method and apparatus.

It is a still further objective of the invention to provide a hierarchical motion estimation method and apparatus in which the hierarchical motion estimation search is conducted using downsampled full pixel values.

It is a still further objective of the invention to provide a hierarchical motion estimation method and apparatus in which the hierarchical motion estimation search is a field search.

SUMMARY OF THE INVENTION

These and other objectives are achieved by the method and apparatus described herein.

According to the invention there is provided a method of temporal compression of a digital video data stream. The method starts by hierarchically searching in at least one search unit for pixels in a reference picture to find a best match macroblock therein corresponding to the current macroblock. In the next step a motion vector is constructed between the best match macroblock and the current macroblock.

According to a further embodiment, there is provided a method of temporal compression of a digital video data stream. The method comprises using downsampled full pixel values to search for pixels in a reference picture to thereby find a best match macroblock. By a best match macroblock is meant a macroblock in a reference picture which most closely resembles the current macroblock. The next step is constructing a motion vector between the best match macroblock and the current macroblock.

According to a still further embodiment of the invention there is provides a method of temporal compression of a digital video data stream comprising field searching with even/even, odd/odd, even/odd, and odd/even field search unit inputs. The search is for pixels in a reference picture field to find a best match macroblock therein corresponding to the current macroblock. As before a motion vector is constructed between the best match macroblock and the current macroblock.

THE FIGURES

The invention may be understood by reference to the FIGURES appended hereto.

FIG. **1** shows a flow diagram of a generalized MPEG2 compliant encoder **11**, including a discrete cosine transformer **21**, a quantizer **23**, a variable length coder **25**, an inverse quantizer **29**, an inverse discrete cosine transformer **31**, motion compensation 41, frame memory **42**, and motion estimation **43**. The data paths include the i^{th} picture input **111**, difference data **112**, motion vectors **113** the picture output **121**, the feedback picture for motion estimation and compensation **131**, and the motion compensated picture **101**. This FIGURE has the assumptions that the i^{th} pictures exists in Frame Memory or Frame Store **42**, and that the $i+1^{th}$ picture is being encoded with motion estimation.

FIG. **2** illustrates the I, P, and B pictures, examples of their display and transmission orders, and forward, and backward motion prediction.

FIG. **3** illustrates the search from the motion estimation block in the current frame or picture to the best matching block in subsequent or previous frame or picture. Elements **211** and **211'** represent the same location in both pictures.

FIG. 4 illustrates the movement of blocks in accordance with the motion vectors from their position in a previous picture to a new picture, and the previous picture's blocks adjusted after using motion vectors.

FIG. 5 illustrates the overall architecture of the search unit, with a Hierarchal Search Unit **201** and a Refinement Search Unit **221**. The Hierarchal Search Unit **201** has a Downsampled Full Pixel Search Unit **203**. The Refinement Search Unit **221** has a Full Pixel Search Unit **223** which provides input to both a Half Pixel Search Unit **225** and a Dual Prime Search Unit **227**. The Dual Prime Search Unit **227** also receives input from the Half Pixel Search Unit **225**.

FIG. 6 shows the hierarchal motion estimation data flow, with a hierarchal search unit **201** receiving best match/difference offset data from a previous hierarchal search unit (not shown) and data from the Current Macro Block (CMB) data bus **205**, and having output to a Refinement Search/Reconstruction Unit **221**, and a Hierarchal Search Memory **211**. The Refinement Search/Reconstruction Unit **221** receives data from the Current Macro Block data bus **205** and sends and receives data to and from the Diff/Qxfrm Data Bus **231** and the Refinement Search Memory **229**. The output of the Refinement Search/Reconstruction Unit **221** is to the Motion Vector Bus **241**.

FIG. 7 shows the Hierarchical Search Unit Data Flow receiving data from the Current Macro Block Data Bus (Luminance Data only **205**), through the Luminance Buffer **207**, and receiving data from and passing data to the Search Data Bus **207**. Four field searches are shown, **f1/f1, 301, f2/f2, 303, f1/f2, 305**, and **f2/f1, 307**. These provide, respectively, the **f1/f1** difference, the **f2/f2** difference, the f1/f2 difference, and the f2/f2 difference. These data go to the Best Match Result Selection Unit, **311**, which outputs the Best Match Difference/Offset **313**.

FIG. 8 shows the Refine-Search/Reconstruction Unit **221** data flow. Chrominance and luminance data enters the unit through the CMB data bus **205** and the LUMA/CHROMA buffer **207** under the control of the Memory Controller **301**. The data goes through the Full Resolution Unit (FR) **321**, and the Half Resolution Unit (HR), **323**, to and through the Dual Prime Unit (DP) **325** to the FD Unit, **327**, and from the FD Unit, **327**, to the Motion Adjust Unit (MA), **329**. The Motion Estimation Processing Unit (MEPROC), **331**, controls these units and sends control signals to the Motion Vector Bus (MV Bus). The output of the FD Unit **327** goes to the Diff/QXFRM Data Bus, **332**, and from there to the Inverse Quantizer (IQ), **333**, and the Inverse Discrete Cosine Transform Unit (ID), **335**, and back to the Motion Adjust Unit (MA), **329**.

FIGS. 9 and 10 shows Table 1 which depicts the motion estimation search strategies, including search mode (hierarchical or non-hierarchical), picture structure (interlaced or progressive), picture type (intra, predicted, bidirectional), motion estimation options (dual prime, non-dual prime), number of searches, search type, and refinement size.

DETAILED DESCRIPTION OF THE INVENTION

Disclosed is a motion estimation architecture which is scalable and efficient, and performs suitably to meet the stringent demands of real time encoding environments.

The invention relates to MPEG and HDTV compliant encoders and encoding processes. The encoding functions performed by an encoder include data input, motion estimation, macroblock mode generation, data reconstruction, entropy coding, and data output. Motion estimation and compensation are the temporal compression functions. They are repetitive functions with high computational requirements, and they include intensive reconstructive processing, such as inverse discrete cosine transformation, inverse quantization, and motion compensation.

More particularly the invention relates to motion estimation, compensation, and prediction, and even more particularly to the calculation of motion vectors. Motion compensation exploits temporal redundancy by dividing the current picture into blocks, for example, macroblocks, and then searching in previously transmitted pictures for a nearby block with similar content. Only the difference between the current block pels and the predicted block pels extracted from the reference picture is actually compressed for transmission and thereafter transmitted.

The simplest method of motion compensation and prediction is to record the luminance and chrominance, i.e., intensity and color, of every pixel in an "I" picture, then record changes of luminance and chrominance, i.e., intensity and color for every specific pixel in the subsequent picture. However, this is uneconomical in transmission medium bandwidth, memory, processor capacity, and processing time because objects move between pictures, that is, pixel contents move from one location in one picture to a different location in a subsequent picture. A more advanced idea is to use a previous picture to predict where a block of pixels will be in a subsequent picture or pictures, for example, with motion vectors, and to write the result as "predicted pictures" or "P" pictures. More particularly, this involves making a best estimate or prediction of where the pixels or macroblocks of pixels of the $i+1^{th}$ picture will be in the i^{th} picture. It is one step further to use both subsequent and previous pictures to predict where a block of pixels will be in an intermediate or "B" picture.

To be noted is that the picture encoding order and the picture transmission order do not necessarily match the picture display order. See FIG. 2. For I-P-B systems the input picture transmission order is different from the encoding order, and the input pictures must be temporarily stored until used for encoding. A buffer stores this input until it is used.

For purposes of illustration, a generalized flow chart of MPEG compliant encoding is shown in FIG. 1. In the flow chart the images of the i^{th} picture and the $i+1^{th}$ picture are processed to generate motion vectors. The motion vectors predict where a macroblock of pixels will be in a prior and/or subsequent picture. The use of the motion vectors instead of full images is a key aspect of temporal compression in the MPEG and HDTV standards. As shown in FIG. 1 the motion vectors, once generated, are used for the translation of the macroblocks of pixels, from the i^{th} picture to the $i+1^{th}$ picture.

As shown in FIG. 1, in the encoding process, the images of the i^{th} picture and the $i+1^{th}$ picture are processed in the encoder 11 to generate motion vectors which are the form in which, for example, the $i+1^{th}$ and subsequent pictures are encoded and transmitted. An input image **111X** of a subsequent picture goes to the Motion Estimation unit **43** of the encoder. Motion vectors **113** are formed as the output of the Motion Estimation unit **43**. These vectors are used by the Motion Compensation Unit **41** to retrieve macroblock data from previous and/or future pictures, referred to as "reference" data, for output by this unit. One output of the Motion Compensation Unit **41** is negatively summed with the output

from the Motion Estimation unit **43** and goes to the input of the Discrete Cosine Transformer **21**. The output of the Discrete Cosine Transformer **21** is quantized in a Quantizer **23**. The output of the Quantizer **23** is split into two outputs, **121** and **131**; one output **121** goes to a downstream element **25** for further compression and processing before transmission, such as to a run length encoder; the other output **131** goes through reconstruction of the encoded macroblock of pixels for storage in Frame Memory **42**. In the encoder shown for purposes of illustration, this second output **131** goes through an inverse quantization **29** and an inverse discrete cosine transform **31** to return a lossy version of the difference macroblock. This data is summed with the output of the Motion Compensation unit **41** and returns a lossy version of the original picture to the Frame Memory **42**.

As shown in FIG. **2**, there are three types of pictures. There are "Intra pictures" or "I" pictures which are encoded and transmitted whole, and do not require motion vectors to be defined. These "I" pictures serve as a source of motion vectors. There are "Predicted pictures" or "P" pictures which are formed by motion vectors from a previous picture and can serve as a source of motion vectors for further pictures. Finally, there are "Bi-directional pictures" or "B" pictures which are formed by motion vectors from two other pictures, one past and one future, and can not serve as a source of motion vectors. Motion vectors are generated from "I" and "P" pictures, and are used to form "P" and "B" pictures.

One method by which motion estimation is carried out, shown in FIG. **3**, is by a search from a macroblock **211** of an i+1th picture throughout a region of the previous picture to find the best match macroblock **213** (**211**' is the same location as **211** but in the previous picture). Translating the macroblocks in this way yields a pattern of macroblocks for the i+1th picture, as shown in FIG. **4**. In this way the ith picture is changed a small amount, e.g., by motion vectors and difference data, to generate the i+1th picture. What is encoded are the motion vectors and difference data, and not the i+1th picture itself. Motion vectors translate position of an image from picture to picture, while difference data carries changes in chrominance, luminance, and saturation, that is, changes in color and brightener.

Returning to FIG. **3**, we look for a good match by starting from the same location in the ith picture **211**' as in the i+1th picture **211**X. A search window is created in the ith picture. We search for a best match within this search window. Once found, the best match motion vectors for the macroblock are coded. The coding of the best match macroblock includes a motion vector, that is, how many pixels in the y direction and how many pixels in the x direction is the best match displaced in the next picture. Also encoded is difference data, also referred to as the "prediction error", which is the difference in chrominance and luminance between the current macroblock and the best match reference macroblock.

FIG. **4** illustrates the movement of blocks in accordance with the motion vectors from their position in a previous picture to a new picture, and the previous picture's blocks adjusted after using motion vectors.

An overview of the architecture of the invention is shown in FIGS. **5** and **6**. As shown in FIG. **5**, a two stage hierarchal processor structure is used, while as shown in FIG. **6**, two-level hierarchal search approach is used.

The Current Macro Block Data Bus (CMB DATA BUS) **205** is used to input current macro block (CMB) luminance data to both the hierarchical search unit **201** and refinement search/reconstruction unit **221**. This bus also provides CMB luminance and chominance data to the refinement search/reconstruction unit.

The hierarchical search unit **201** shown is normally used to perform its search operations using downsampled CMB data. The user may select the extent to which the data is downsampled, from a maximum of 4:1 horizontally to a minimum of 1:1 (i.e. non-downsampled). The number of such units used is scalable (1, 2 or 4) depending on the search range desired. The hierarchical search unit **201** stores and fetches luminance search data for both I- and P-frames in a hierarchical search memory. The size of the hierarchical search memory **211** is dependent on the extent to which the picture data is downsampled. The luminance search data stored is equivalent to the input current macroblock (CMB) data with downsampling applied if selected by the user. Upon completion of its search, the hierarchical search unit outputs the best match search result for a given current macroblock (CMB) based on the minimum absolute difference and its corresponding offset relative to the current macroblock (CMB) position, via the best match diff/offset bus. The description above is for luminance, but can also apply to chrominance and/or luminance and chrominance data.

The refinement search/reconstruction unit **221** shown in FIGS. **5**, **6**, and **8** can operate in either a standalone environment (i.e., no hierarchical search unit attachment) for IP encoding or with a hierarchical search unit attached for IPB encoding. This unit **221** uses non-downsampled current macroblock (CMB) luminance data to perform its search operations against reconstructed past and/or future I- and P-frame data contained in the refinement search memory. Upon completion of its search, the refinement-search/reconstruction unit outputs either intra current macroblock (CMB) luminance and chrominance pixel data or non-intra current macroblock (CMB) luminance and chrominance minus the best match Refinement MB (RMB) luminance and chrominance pixel difference data on the DIFF/QXFRM DATA BUS **231**. Furthermore, when non-intra difference data is output, the motion vector corresponding to the location of the best match reference macroblock (RMB) location relative to the current macroblock (CMB) location is output on the motion vector bus (MV BUS) **241**.

Upon completion of the discrete cosine transformation (DCT) and quantization on the output intra data or non-intra difference data, the transformed luminance and chrominance blocks are input to the refinement-search/reconstruction unit via the DIFF/QXFRM DATA BUS **231** to allow the refinement-search/reconstruction unit **221** to properly reconstruct I- and P-frame data which is output to the refinement search memory. Extensive pipelining is utilized within each unit in order to meet the performance requirements for a real time encoding environment.

The overall search strategy adopted by the disclosed motion estimation architecture is broken down into the following pipelined components shown in FIGS. **6** and **8**.

As shown in FIGS. **6** and **8**, the hierarchical search unit **201** performs a typical search using downsampled (averaged) full pixel values. After the best downsampled match is determined using non-reconstructed current macroblock (CMB) data from past and/or future I- and P-frames, the refinement search unit **221** performs a non-downsampled full pixel search using reconstructed refinement search data around the offset of the best downsampled match. After the best non-downsampled full pixel match is determined, both half pixel and, optionally, dual prime (DP) refinement searches are performed using reconstructed refinement data

based on the location of the best non-downsampled full pixel match. Based on the best match motion estimation result as determined by the minimum absolute difference value, the original current macroblock (CMB) or best match difference macroblock luminance and chrominance data is output if the macroblock is to be coded as intra or non-intra, respectively. Three different non-intra results are possible:

CMB-RMB Full Pixel Best Match

CMB-RMB Half Pixel Best Match

CMB-RMB Dual Prime Best Match

The Hierarchical Search Unit is shown in FIGS. **5** and **6**,. The dataflow diagram for this unit is illustrated in FIG. **7**. As shown in the figure, current macroblock (CMB) luminance data is stored in the LUMA BUFFER **207**. Downsampling of the data occurs at this point. In order to offer the user as much flexibility as possible in terms of search range and search memory size, the following downsampling options are available:

- 4:1—Stores four pixels for each pixel row of a MB by taking the average of every four successive pixel values of a row. This affords the largest search window per unit (+/−64 Horizontal, +/−56 Vertical) and requires the least amount of search memory (0.25 MB for two search reference frames).
- 2:1—Stores eight pixels for each pixel row of a MB by taking the average of every two successive pixel row values of a row. This affords the next largest search window per unit (+/−32 Horizontal, +/−32 Vertical) and requires the next largest amount of search memory (0.5 MB for two search reference frames).
- 1:1—Stores sixteen pixels for each pixel row (non-downsampled). This affords the smallest search window per unit (+/−16 Horizontal, +/−16 Vertical) and requires the largest amount of search memory (1 MB for two search reference frames).

The CMB data in either its downsampled or non-downsampled form is output from the LUMA BUFFER **207** to four FIELD SEARCH units, **301**, **303**, **305**, and **307**, as shown in FIG. **7**. For I- and P-pictures, the current macroblock (CMB) data is also output to the hierarchical search memory via the search data bus. Note that the current macroblock (CMB) data is not output to the hierarchical search memory for B-pictures since the MPEG-2 standard precludes B-pictures from serving as reference frames. Search memory data for all macroblocks contained in the search window is also input to the four field search units. When using only one hierarchical search unit, the search data is fetched so that the search macroblock (SMB) at the center of the search window is at the same position as the CMB against which the search operation is being performed. When using two or four hierarchical search units, the search data is fetched so that the search macroblock (SMB) at the center of the combined search window among all the units is located at the previous picture's average motion vector offset position from the CMB location.

Field searching is done in the hierarchical search unit as shown in FIG. **7**. The f1/f1 field search unit **301** handles searching of the current macroblock (CMB) odd lines against the search data odd lines. The f2/f2 field search unit **303** handles searching of the current macroblock (CMB) even lines against the search data even lines. The f1/f2 field search unit **305** handles searching of the current macroblock (CMB) odd lines against the search data even lines. The f2/f1 field search unit **307** handles searching of the current macroblock (CMB) even lines against the search data odd lines.

For each difference value output by these units, two additional frame search results are generated by combining the f1/f1 and f2/f2 field search results, and the f1/f2 and f2/f1 field search results. Each result is input to the best match result selection unit **311**. The first step performed by this unit **311** is to add a weighting factor, referred to as the base weight, to each result. The base weight value varies according to the offset position of the search macroblock (SMB) relative to the previous picture's average motion. The farther away a given search macroblock (SMB) is relative to the previous picture's average motion vector offset from the current macroblock (CMB) position, the larger the base weight added to that search location's result. Thus, the search tends to favor SMB positions which most closely follow the previous picture's average motion trajectory.

The number of results output by this unit on the best match diff/offset bus is dependent on the format of the picture being searched. For frame (progressive) format searches, five results are output: four Best Match Field Search Results (f1/f1, f2/f2, f1/f2, f2/f1), one Best CMB Frame Search Result (minimum of f1/f1+f2/f2 diff and f1/f2+f2/f1 diff). For field (interlaced) format searches, two results are output: Best current macroblock (CMB) Same Parity Frame Search (minimum f1/f1+f2/f2 diff), Best CMB Opposite Parity Frame Search (minimum f1/f2+f2/f1 diff).

Furthermore, when performing search operations for B-pictures, two sets of these results are produced (one set for the past reference search, one set for the future reference search). In addition to the minimum absolute difference value, the offset location of the SMB which produced the minimum value is output.

As mentioned previously, multiple hierarchical search units can be used to increase the search window size. When two hierarchical search units are employed, a maximum search window size of +/−128 Horizontal, +/−56 Vertical or +/−64 Horizontal and +/−112 Vertical can be defined using 0.5 MB of search memory. When the maximum of four of these units are employed, a maximum search window size of +/−128 Horizontal, +/−112 Vertical can be defined using 1 MB of search memory. In a multiple hierarchical search unit configuration, the best match diff/offset results are passed in a daisy-chain fashion from one unit to another. In such a configuration, the first sender unit at the end of the daisy-chain passes its absolute difference and offset results to the first receiver unit. The first receiver unit compares its search results against those received from the first sender unit, and in turn transmits the minimum absolute difference and offset results to the second receiver unit. This process continues until the last receiver in the chain passes the final minimum absolute difference and offset results to the refinement search/reconstruction unit.

The Refinement Search/Reconstruction Unit is shown in FIGS. **5**, **6**, and **8**. The dataflow diagram for this unit is illustrated with specificity in FIG. **8**. As illustrated in the figure, current macroblock (CMB) luminance and chrominance data is received from the CMB DATA BUS **205** and stored in the LUMA/CHROMA BUFFER **207**. The luminance data is the same as that received by the hierarchical search unit described previously. In order to most effectively pipeline the motion estimation process, the buffer is designed to hold luminance data for two MBs and chrominance data for one MB.

The first motion estimation refinement step performed occurs in the Full Resolution (FR) Unit **321**. This unit fetches current macroblock (CMB) luminance data from the LUMA/CHROMA BUFFER **207** and Reference Macroblock (RMB) luminance data pertaining to the full pixel refinement search window from the refinement search memory via the MC (Memory Controller) Unit **301**. The

control information (address and fetch size) required by the full resolution unit (FR) **321** to perform the refinement data fetch is setup by the Motion Estimation Processing Unit (MEPROC) **331** based on whether a hierarchical or non-hierarchical (i.e., no hierarchical search unit) search is being performed. When operating in non-hierarchical search mode, the Motion Estimation Processing Unit (MEPROC) **331** centers the full pixel refinement search about the location of the current macroblock (CMB). When operating in hierarchical search mode, the Motion Estimation Processing Unit (MEPROC) **331** uses the hierarchical search unit results received across the BEST MATCH DIFF/OFFSET bus **330** in order to center the full pixel refinement search about the offset location. In order to meet real time performance requirements, the number and types of searches performed and the search window size vary depending on the search mode (hierarchical or non-hierarchical), picture structure and type, and motion estimation options selected by the user. Table 1 summarizes this information. Note that motion estimation searches are performed for I-pictures in order to generate error concealment motion vectors which the user may select to insert in the compressed bitstream.

In Table 1, Hier refers to hierarchical search mode, Non-Hier refers to non-hierarchical search mode, DP refers to Dual Prime motion estimation, x Ref refers to whether 1 (opposite parity) or 2 (same parity and opposite parity) reference fields are specified for searching, OP refers to reference macroblock (RMB) field data of opposite parity with respect to the parity of the current macroblock (CMB), SP refers to reference macroblock (RMB) field data of the same parity with respect to the parity of the current macroblock (CMB), (PR) refers to the past refinement search data stored in refinement search memory, (FR) refers to the future refinement search data stored in refinement search memory, (BR) refers to the bidirectional interpolation (averaging) between past and future refinement search data stored in refinement search memory, f1/f1 refers to odd line refinement data used to search current macroblock (CMB) odd field lines, f1/f2 refers to even line refinement data used to search current macroblock (CMB) odd field lines, f2/f1 refers to odd line refinement data used to search current macroblock (CMB) even field lines, f2/f2 refers to even line refinement data used to search current macroblock (CMB) even field lines, f1/fx refers to either odd or even line refinement data used to search current macroblock (CMB) odd field lines based on whether the f1/f1 or f1/f2 hierarchical search unit result, respectively, produced the better match, and f2/fx refers to either odd or even line refinement data used to search current macroblock (CMB) even field lines based on whether the f2/f1 or f2/f2 hierarchical search unit result, respectively, produced the better match. Upon determining the absolute difference value for each search location, a base weight factor is added to each result in the same manner as described for the hierarchical search unit. The final best match result for each type of search performed is determined by the minimum absolute difference plus base weight value.

Upon completion of its search operations, the FR Unit outputs the CMB data along with enough refinement data surrounding each RMB best match to perform up to eight half pixel MB searches. For interlaced pictures, either one (OP Field) or two (SP Field, OP Field) best match reference macroblock (RMB) search areas are output, while for progressive pictures, two field best match reference macroblock (RMB) search areas (best CMB f1 match, best CMB f2 match) and one best match reference macroblock (RMB) frame search area are output. Note that a 44 bit bus is used to transmit the best match reference macroblock (RMB) search area data since each reference macroblock (RMB) best match pixel value is represented by an 11-bit byte when bidirectional reference macroblock (RMB) data produces the best match in a B-picture (refer to U.S. patent application Ser. No. 08/411,100 and U.S. patent application Ser. No. 08/602,472, both hereby incorporated herein by reference). In addition, the best match absolute difference and offset results for each best match RMB search area are output to the MEPROC Unit.

A second motion estimation refinement step performed occurs in the Half Resolution (HR) Unit **323**. This unit performs a refinement search for up to eight half pixel reference macroblocks (RMBS) which surround the best match full pixel reference macroblock (RMB) as determined by the full resolution (FR) Unit **321**. Upon determining the best match half pixel reference macroblock (RMB) location (i.e., the one which produced the minimum absolute difference value) for a particular search operation, both the best match absolute difference value and its corresponding half pixel offset are output to the motion estimation processor unit (MEPROC) Unit **331**. The motion estimation processor (MEPROC) Unit **331** then compares the best match absolute difference values received from the full resolution (FR) **321** and half resolution (HR) Units **323**, and instructs the half resolution (HR) Unit **323** to output the reference macroblock (RMB) full or half pixel luminance data which produced the minimum absolute difference value for each search operation performed. The half resolution unit (HR Unit) outputs this data, along with the corresponding current macroblock (CMB) data, to the dual prime unit (DP Unit).

Another motion estimation refinement step which is performed occurs in the Dual Prime Unit (DP) **325**. This unit can be configured to perform Dual Prime refinement using current macroblock (CMB) and reference macroblock (RMB) data from either the full resolution (FR) or half resolution (HR) Unit **323**. Furthermore, for interlaced (field) pictures, the unit may be configured to use either the same or opposite parity reference macroblock (RMB) when two reference fields are supplied. By using the default mode which performs Dual Prime motion estimation using full resolution unit (FR Unit) **321** current macroblock (CMB) and reference macroblock (RMB) data, two advantages are realized:

First, performance is optimized since the half resolution (HR) **323** and dual prime (DP) **325** unit search operations will occur in parallel.

Second, for progressive (frame) pictures, the invalid case in which the half resolution (HR) reference macroblock (RMB) frame best match involves vertical interpolation between opposite parity fields is eliminated. This increases the probability that valid Dual Prime refinement can be performed for a given current macroblock (CMB) from 33% to 100%.

Based on the offset information received from the hierarchical search unit, the full resolution unit (FR Unit) **321** and the half resolution unit (HR Unit) **323** (if selected for providing data for Dual Prime refinement to the DP Unit **325**), the motion estimation processor (MEPROC) **331** formulates a motion vector which points to the Dual Prime reference macroblock (RMB). The motion estimation processor (MEPROC) **331** then performs the appropriate motion vector scaling operations and converts the scaled vector(s) into the appropriate refinement search memory location(s) from which to fetch additional luminance refinement search data used to perform Dual Prime motion estimation. Once the Dual Prime best match is determined,

both the corresponding absolute difference value and offset are output to the motion estimation processor (MEPROC) Unit **331**. The motion estimation processor (MEPROC) Unit **331** then decides which of the stet three results produced the overall best match depending on the picture structure as follows:

Progressive

Best Match Frame Reference Macroblock (RMB),

Best Match Combined f1 and f2 Field Reference Macroblock (RMB),

Best Match Dual Prime Reference Macroblock (RMB).

Interlaced Best

Match Opposite Parity Field Reference Macroblock (RMB),

Best Match Same Parity Field Reference Macroblock (RMB),

Best Match Dual Prime Reference Macroblock (RMB).

The motion estimation processor (MEPROC) **331** informs the dual prime (DP) unit **325** which reference macroblock (RMB) result to output to the FD Unit **327**. At this point, the refinement motion estimation phase is complete.

The next unit which starts the macroblock (MB) reconstruction phase is the FD Unit **327**. This unit gathers current macroblock (CMB) and the best match reference macroblock (RMB) luminance data from the dual prime (DP) Unit **325** and fetches the corresponding current macroblock (CMB) chrominance data from the LUMA/CHROMA BUFFER **207**, and fetches reference macroblock (RMB) chrominance data from the refinement search memory for non-intra coded macroblocks. Based on information received from the motion estimation processor (MEPROC) **331** indicating whether the current macroblock (CMB) is to be coded as intra or non-intra, this unit will process the luminance and chrominance data in different ways. If the decision is intra (no motion), then the FD Unit will output current macroblock (CMB) luminance and chrominance data directly to the DIFF/QXFRM DATA BUS **332**, and send reference macroblock (RMB) luminance and chrominance data of all '00's to the MA (Motion Adjust) Unit **329**. If the decision is non-intra (motion), then the FD Unit **327** will output CMB-RMB luminance and chrominance data to the DIFF/QXFRM DATA BUS, and send the selected reference macroblock (RMB) luminance and chrominance data to the motion adjust (MA) Unit **329**. In the non-intra case, the motion estimation processor (MEPROC) Unit **331** initializes refinement search memory pointers in the FD Unit **327** to fetch the required reference macroblock (RMB) chrominance data so that the CMB-RMB chrominance difference can be calculated. Note that the FD Unit is responsible for proper arbitration of the DIFF/QXFRM DATA BUS **332**. This is accomplished by assuring that the luminance (or chrominance) data transmitted by this unit is returned in its entirety to the IQ (Inverse Quantization) Unit **333** prior to transmission of the next chrominance (or luminance) data. The data output by the FD Unit **327** is additionally tagged with a motion vector by the motion estimation processor (MEPROC) Unit **331** for non-intra macroblocks. The motion vector data is output by the motion estimation processor (MEPROC) Unit to the motion vector bus (MV BUS).

Upon application of the discrete cosine transform (DCT) and quantization transforms to the data output by the FD Unit, this data is returned in block format to the IQ (Inverse Quantization) Unit **333** for reconstruction (decoding) of the transformed and quantized data. Both the IQ **333** and ID (Inverse DCT) **335** Units perform the inverse quantization and inverse discrete cosine transform functions specified by the MPEG-2 standard. Thus, a lossy version of the original luminance and chrominance MB data output by the FD Unit **327** is obtained which exactly corresponds to how an external MPEG-2 decoder will uncompress the macroblock. This lossy luminance and chrominance macroblock data is sent to the MA (Motion Adjust) Unit, which adds to this data the reference macroblock (RMB) data which it previously received from the FD Unit. The resultant luminance and chrominance macroblock data is then output to the refinement search memory via the MC Unit for all I- and P-pictures which are processed.

While our invention has been described with respect to certain preferred embodiments and exemplifications, it is not intended to limit the scope of the invention thereby, but solely by the claims appended hereto.

We claim:

1. A method of temporal compression of a digital video data stream, comprising the steps of:

hierarchically searching in at least one heirarchical search unit for pixels in a reference picture to find a best match macroblock therein corresponding to a current macroblock;

constructing a motion vector of offset between the best match macroblock and the current macroblock;

passing the motion vector from the at least one heirarchical search unit to a refinement search unit; and

performing a refinement search around the offset of the best match macroblock.

2. The method of claim **1** comprising conducting multiple hierarchical searches in multiple search units to increase search window size.

3. The method of claim **2** comprising passing best match macroblock difference and offsets in daisy chain fashion from one search unit to the next search unit.

4. A method of temporal compression of a digital video data stream comprising using downsampled full pixel values to search for pixels in a reference picture to find a best match macroblock therein corresponding to a current macroblock, and constructing a motion vector of offset between the best match macroblock and the current macroblock and thereafter conducting a non-downsampled full pixel search using reconstructed refinement search data around the offset of the best match macroblock.

5. The method of claim **4** comprising using 2:1 downsampled pixel values, or 4:1 downsampled pixel values.

6. The method of claim **4** wherein the next picture is to be intra coded and the output is the original current macroblock.

7. The method of claim **4** where the next picture is to be bidirectionally coded or prediction coded and the output is the best match difference macroblock.

8. The method of claim **4** further comprising searching for the best match macroblock using nonreconstructed reference macroblock data.

9. The method of claim **4** further comprising thereafter performing a half pixel search using reconstructed refinement data based on the offset of the best match non-downsampled full pixel best match macroblock.

10. The method of claim **9** further comprising performing a dual prime search.

11. A method of temporal compression of a digital video data stream, comprising the steps of:

field searching with even/even, odd/odd, even/odd, and odd/even field search unit inputs;

forming a same parity frame search by combining the even/even and odd/odd searches;

forming an opposite parity frame search by combining the even/odd and odd/even searches;

selecting a best match macroblock from the search units and the frame searches; and

constructing a motion vector between the best match macroblock and the current macroblock.

12. A search processor for digital video motion estimation, said search processor comprising:

a hierarchical search unit; and

a refinement search unit connected to the heirarchical search unit via a best match diff/offset bus.

13. The search processor of claim 12 wherein said heirarchical search unit comprises downsample full pixel search means.

14. The search processor of claim 12 wherein said refinement search unit comprises full pixel search means, half pixel search means, and dual prime search means, said full pixel search means in series with said half pixel search means and said dual prime search means, and said half pixel search means in series with said dual prime search means.

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